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Role of Probabilistic Micromechanics Modeling in Establishing Design Allowables in Composites

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One of the major challenges in designing with any new material, and particularly with advanced composite materials, is the fidelity of material design allowables. In the case of composite materials, the concern arises from the inherent nature of these materials, i.e., their heterogeneous make-up and the various factors that affect their properties in a specific design environment. Composites have various scales – micro, macro, laminate and structural, as well as numerous other fabrication related parameters. Many advanced composites in aerospace applications involve complex two- and three-dimensional fiber architectures and requires high-temperature processing. Since there are uncertainties associated with each of these, the observed behavior of composite materials shows scatter. Evaluating the effect of each of these variables on the observed scatter in composite properties solely by testing is cost and time prohibitive. One alternative is to evaluate these effects by computational simulation.

The authors have developed probabilistic composite micromechanics techniques by combining woven composite micromechanics and Fast Probability Integration (FPI) techniques to address these issues. In this paper these techniques will be described and demonstrated through selected examples. Results in the form of cumulative distribution functions (CDF) of the composite properties of a MI (melt-infiltrated) SiC/SiC (silicon carbide fiber in a silicon carbide matrix) composite will be presented. A CDF is a relationship defined by the value of the property (the response variable) with respect to the cumulative probability of occurrence. Furthermore, input variables causing scatter are identified and ranked based upon their sensitivity magnitude. Sensitivity information is very valuable in quality control. How these results can be utilized to develop design allowables so that these materials may be used by structural analysts/designers will also be discussed.

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Background

- Advanced composites, specifically high-temperature ceramic matrix composites (CMC's) are candidate materials for a variety of high-performance applications that operate in harsh environments.
- One of the major challenges in designing with any new material, and particularly with advanced composites, is the fidelity of material design parameters.
- Composite materials are heterogeneous in their make-up and various factors affect their properties in a specific design environment.

General Observations

- Composites have many scales – micro, macro, laminate and structural. They also involve numerous other fabrication related parameters.
- Many advanced composites involve complex two- or three-dimensional fiber architectures and generally require a complex multi-step high-temperature processing.
- Since there are uncertainties involved with each of these steps, the observed behavior of composite material exhibits significant scatter.
- Evaluating the effect of the influence of uncertainties in each of these variables solely by testing is cost/time prohibitive.

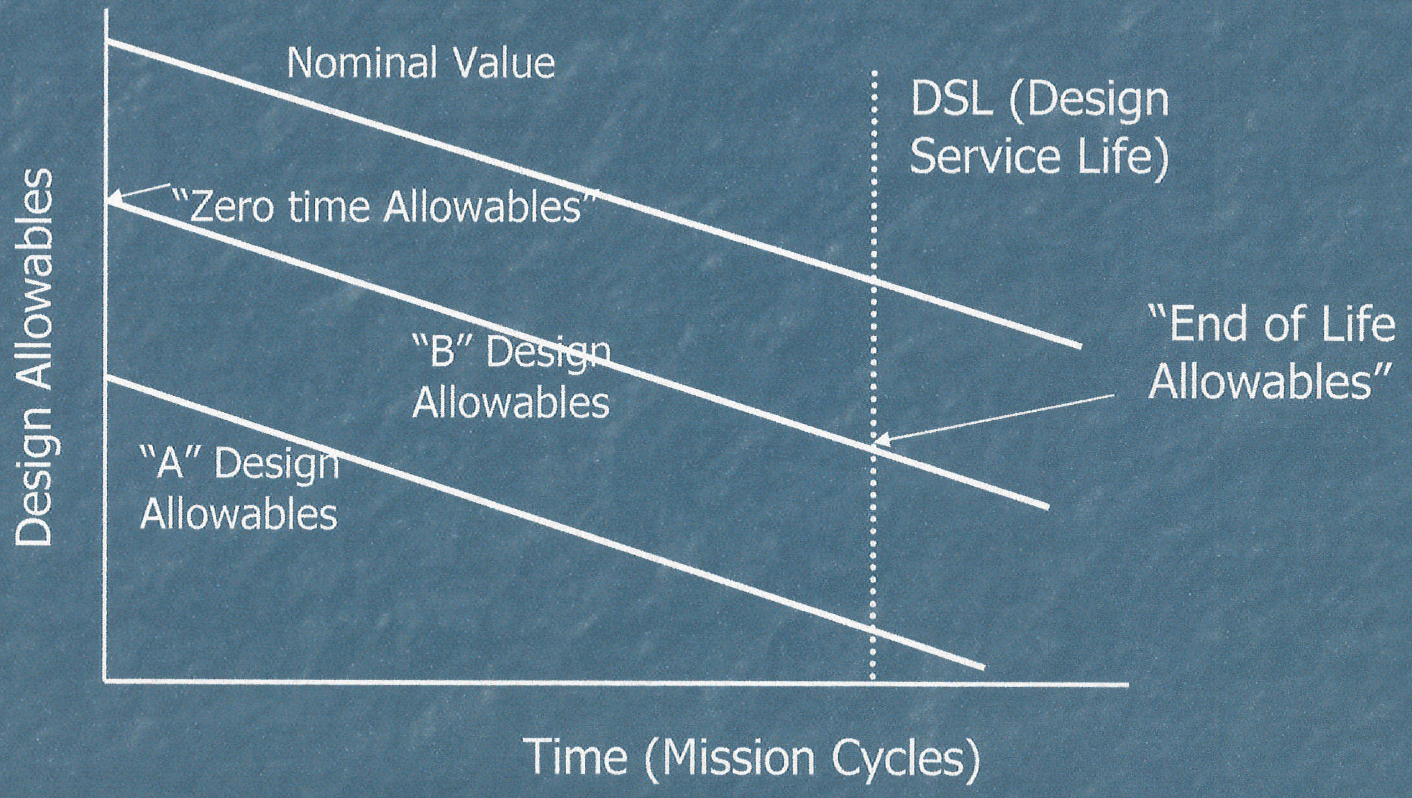
Objectives

- Design the material including uncertainties in constituent as well as fabrication related parameters
- Design structural components in the presence of uncertainties due to loading, environment as well as uncertainties in the material properties.
- Develop quantitative tools for risk assessment of new structural designs using these advanced composite materials.

Technical Challenges

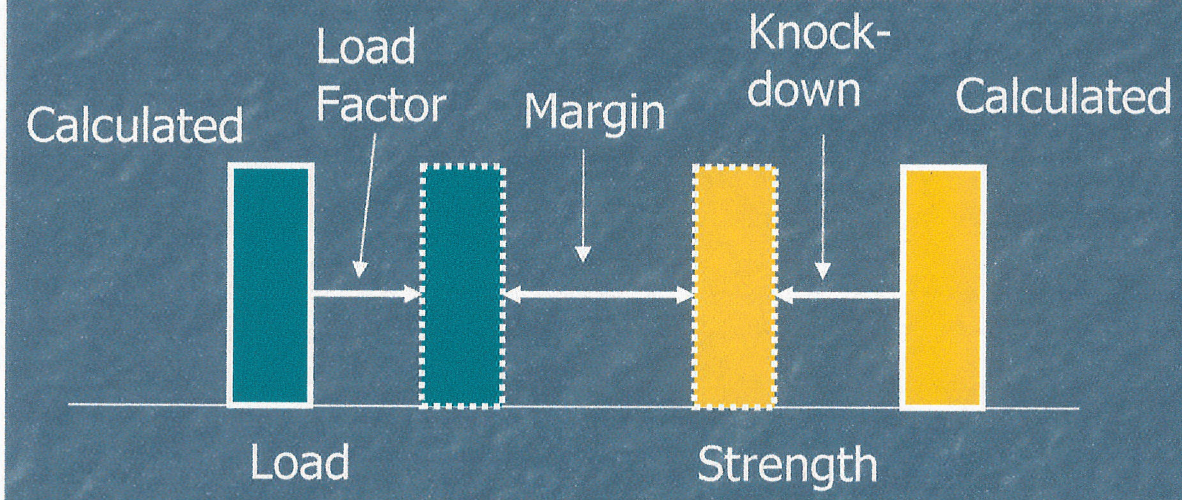
- Cost of generating statistically meaningful data is prohibitive, particularly for advanced high-temperature composites.
- Sparse data on uncertainty distributions.
- High computation burden of probabilistic methods (i.e. efficient design algorithms/tools needed to provide quantifiable risk assessment).

Technical Challenges (contd.)



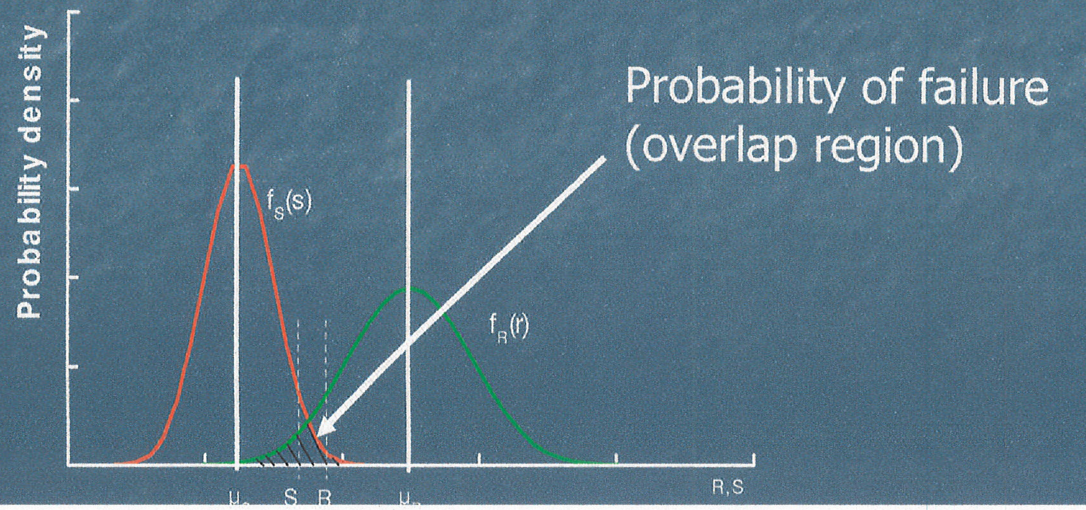
Traditional and Probabilistic Approaches

Traditional "Factor of Safety" Approach

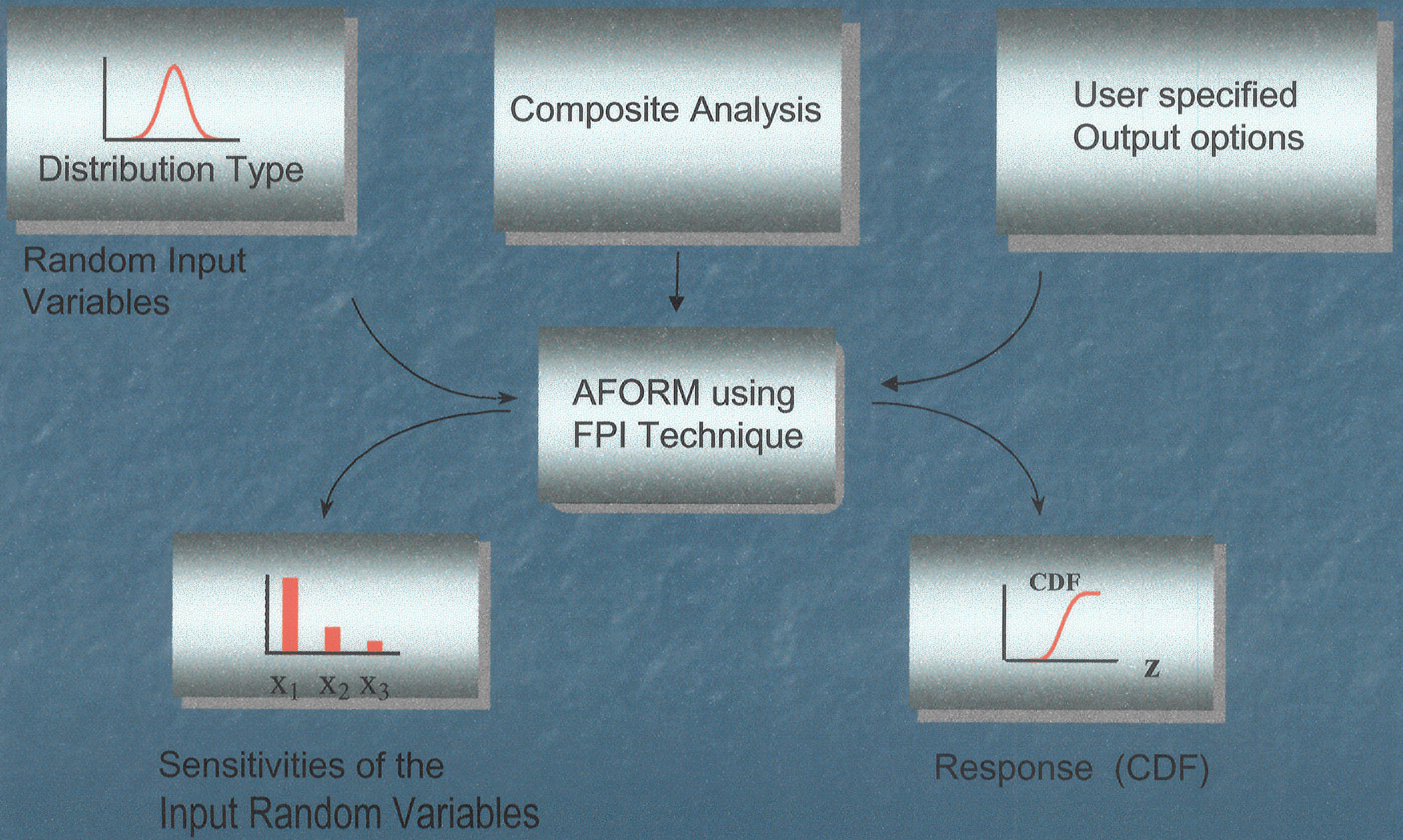


- Unknown or unquantifiable risk
- No insight into risk associated with new materials/technologies

Probabilistic Approach

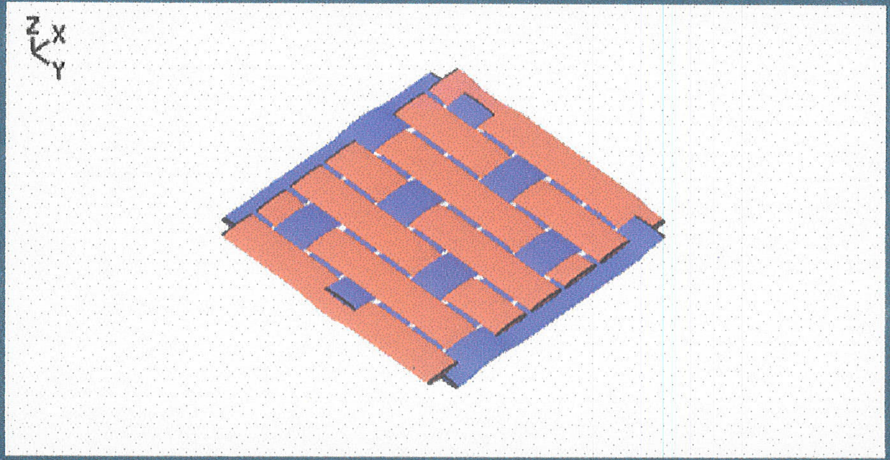


Probabilistic Analysis Flowchart



SiC/SiC Material

- 2-D 0/90 five-harness satin cloth
- Sylramic fiber with BN coating, CVI-SiC overcoat with a melt-infiltrated silicon carbide (MI-SiC) matrix.
- Fiber volume fraction ~ 0.4.



Random Variables

Variable	Mean Value	Standard Deviation	Distribution
Young's modulus (GPa)			
Syramic fiber	359	17.9	Normal
CVI-SiC	400	20	
MI-SiC	324	16.6	
BN coating	69	3.5	
Thermal conductivity (W/m.K)			
Sylramic fiber	20.4	2.1	
CVI-SiC	27	2.8	
MI-SiC	29.4	2.9	
BN coating	6.4	0.6	
BN thickness, fraction of nominal filament dia.	0.1	0.01	
Fiber volume fraction, %	42	2	

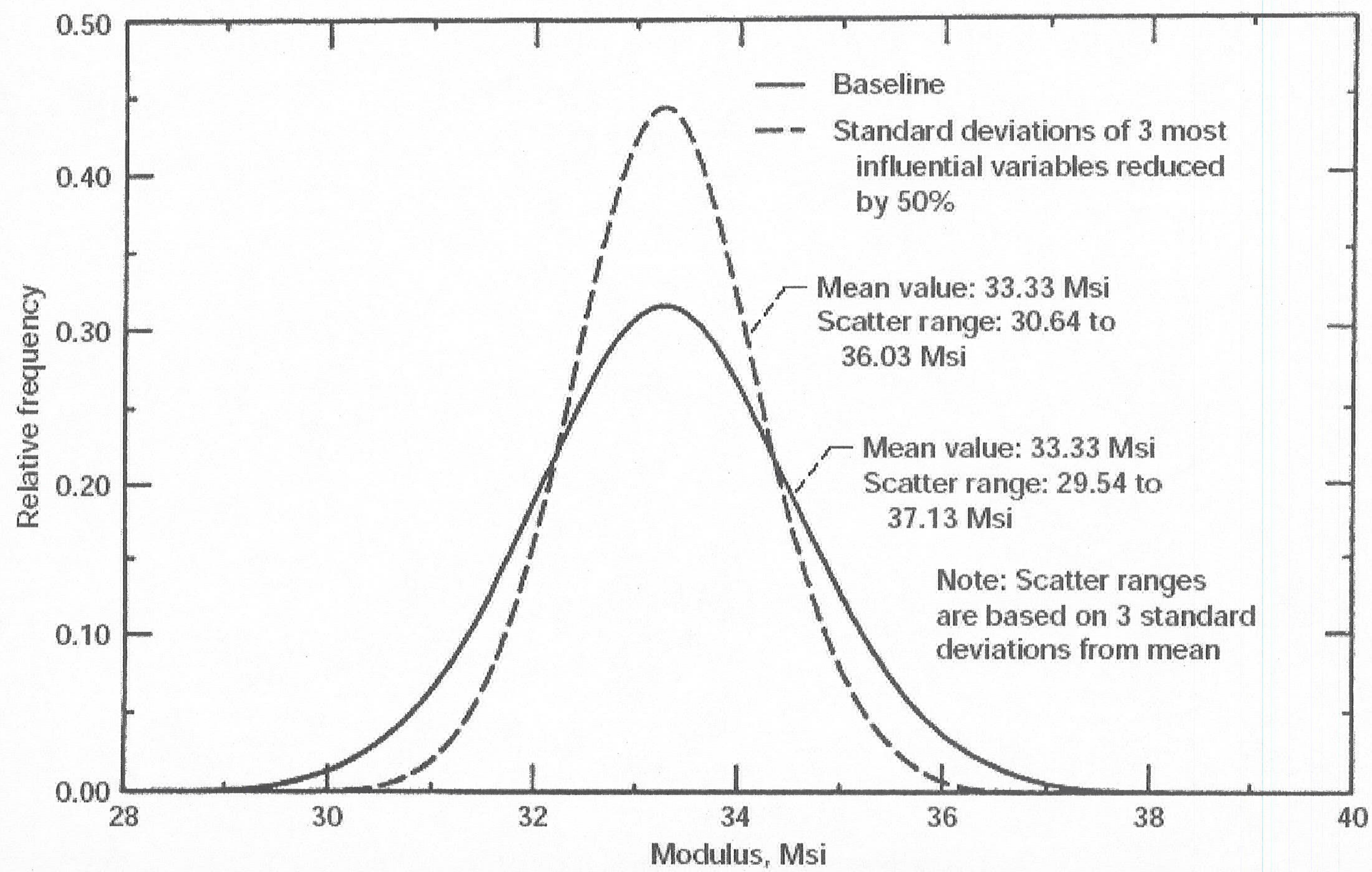
Random Variables

TABLE I.—PRIMITIVE INPUT VARIABLES DISTRIBUTION PARAMETERS

Variable	Mean value	Standard deviation	Distribution
Young's modulus, (Msi)			
Sylramic fiber	52	±2.6	Normal
CVI-SiC	58	±2.9	
MI-SiC	47	±2.4	
BN	10	±0.5	
Thermal conductors (Btu/ft-hr-°F)			
Sylramic fiber	11.8	±1.2	
CVI-SiC	15.6	±1.6	
MI-SiC	16.9	±1.7	
BN	2.0	±0.2	
Coefficient of thermal exponent (ppm/°F)			
Sylramic fiber	6.0	±0.60	
CVI-SiC	6.0	±0.60	
MI-SiC	6.2	±0.62	
BN	3.7	±0.37	
BN thickness (percent within tow)	10	±1	
Fiber tow spacing (ends/in.)	22	±1	
Fiber volume fraction (percent overall)[a]	42	±2	
Void volume fraction (percent within tow)	9	±1	

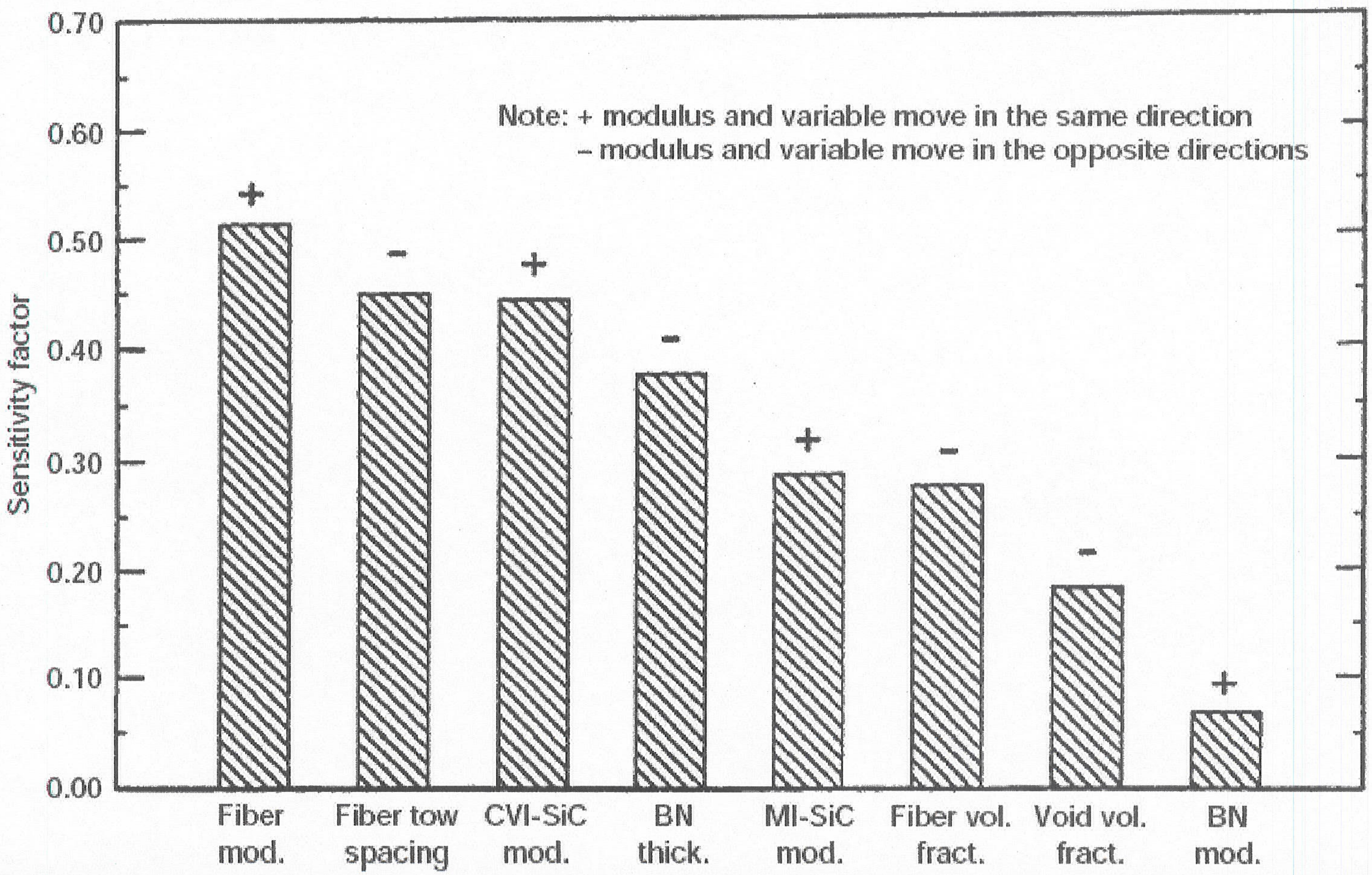
[a]Assume volume fraction of MI-SiC matrix stays constant at 13 percent. Fiber and void volume fraction varies at the expense of CVI-SiC.

Probability Density of In-plane Modulus @ 1100 ^0C

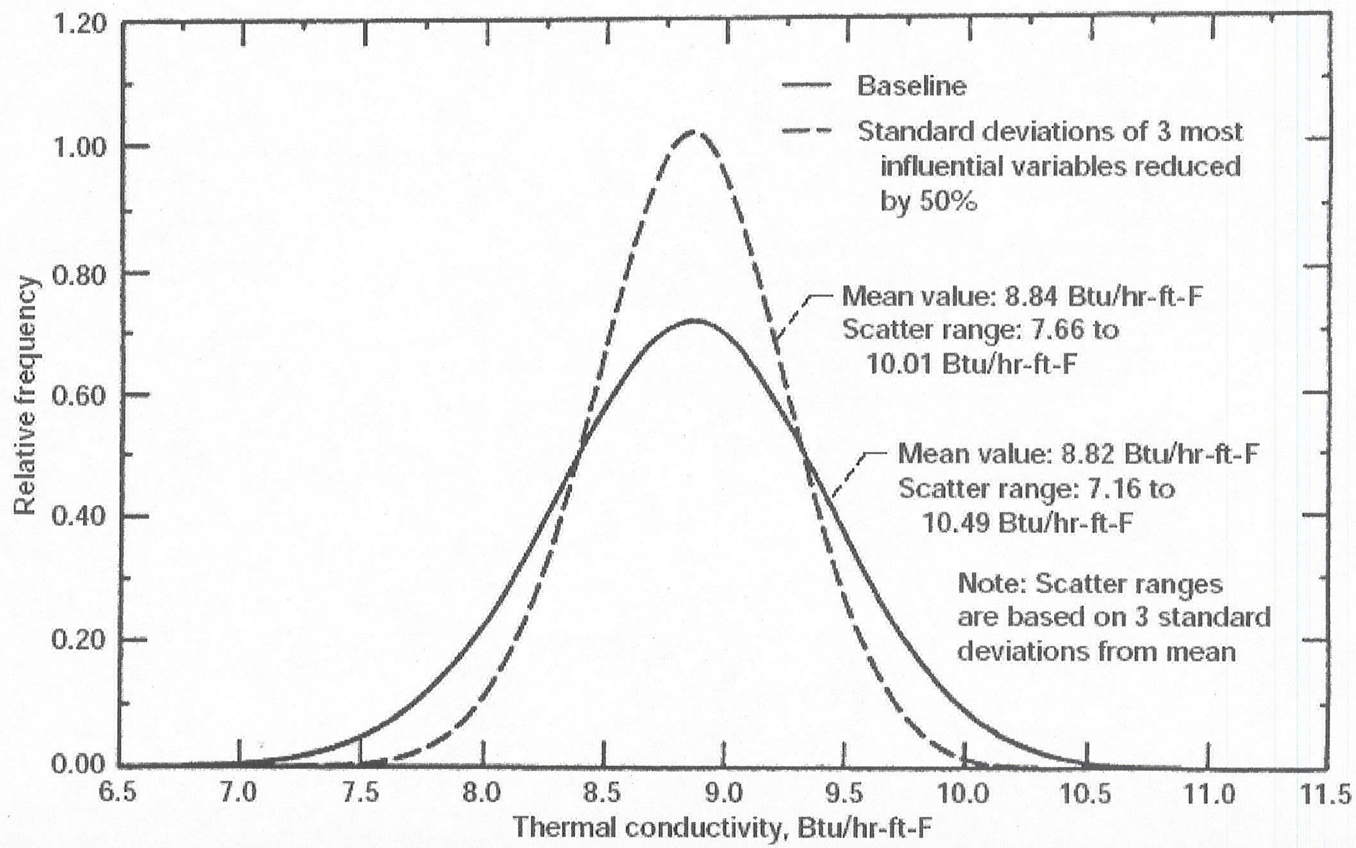


1 Msi = 6.9 GPa

Sensitivity Factors of In-plane Modulus @ 1100 ^{0}C

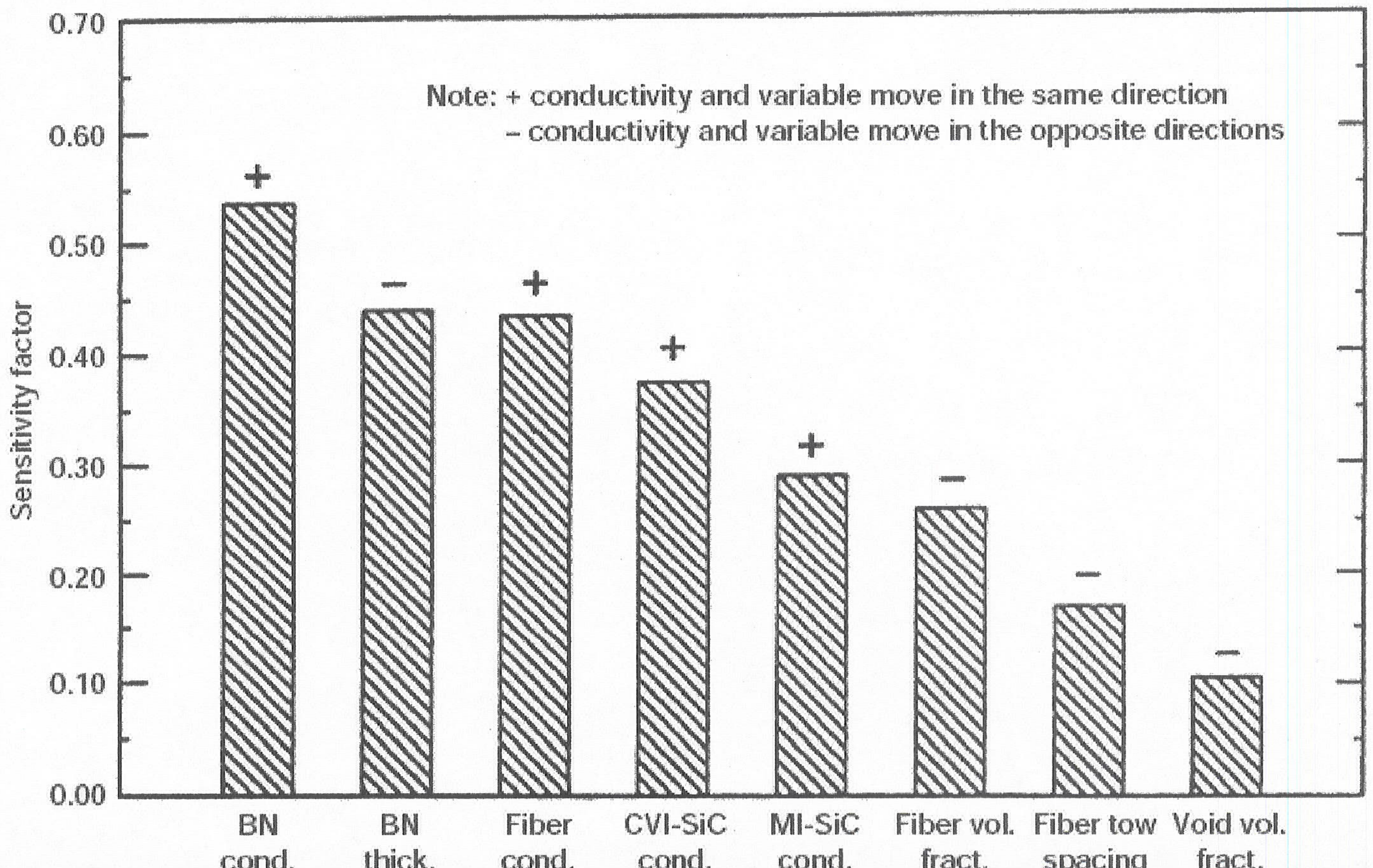


Probability Density of Through-thickness Thermal Conductivity @ 1100 ^0C



1 Btu/hr-ft-F = 1.73 W/m.K

Sensitivity Factors of Through-thickness Thermal Conductivity @ 1100 ^{0}C



Summary

- An integrated probabilistic analysis approach combining CMC woven composite micromechanics and Fast Probability Integration (FPI) techniques was presented.
- Influences of select random variables on key composite thermal/mechanical properties were quantified.
- Results provide key response variables that can help reduce the scatter in the observed composite properties. Economic constraints are not considered.
- Results helpful for structural analyses, material development and guidance in planning resources for data collection etc. to optimize key composite properties.